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# Tuning the charge states in InAs/GaSb or InAs/GaInSb composite quantum wells by persistent photoconductivity

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We have experimentally studied the persistent photoconductivity (PPC) in inverted InAs/GaSb and InAs/GaInSb quantum wells, which can be tuned into a bulk-insulating state by electron-hole hybridization. Specifically we tune the bulk band structure and carriers with light-emitting diode (LED) illuminations. The persistent photoconductivity could be negative or positive, depending on the specific doping structure and the illuminating photon energy. Compared to the widely-used electro-statically gating method, our findings provide a more flexible and non-invasive way to control the band structures and charge states in InAs/GaSb and InAs/GaInSb quantum wells (QWs).  [http://dx.doi.org/10.1063/1.4993894]

Quantum spin Hall insulators (QSHIs), also known as two-dimensional (2D) topological insulators (TIs), is a novel matter characterized by insulating bulk and gapless helical edge states.[1–4] Hybridized InAs/GaSb quantum wells (QWs) and InAs/GaInSb QWs have been proved to support the quantum spin Hall states.[5–10] Under appropriate conditions,[11,12] the band structure in such composite QWs is inverted, and at the cross points of the valence band and conduction band, the density of electrons equals to that of holes, which is labeled as $n_{\mathrm{cross}}$. The holes in GaSb (or GaInSb) layer strongly couple with the electrons in InAs layer, resulting in opening up a bulk hybridization gap with gapless helical edge channels. When the Fermi level sweeps over the hybridized bulk gap by gates, the measured longitudinal resistance $R_{xx}$ shows a peak. The peak has quantized value for the case of the helical edge length within the coherence length.[7,8] Although gating is the most common way to tune the Fermi level, certain studies some researches such as optical measurements and scanning probe studies cannot be readily carried out on top-gated samples. We have developed an alternative method to tune the Fermi level of the (electron and hole) carriers in Inverted InAs/GaSb or InAs/GaInSb QWs with LED illuminations.

Persistent photoconductivity (PPC) is a well-known effect for semiconductor heterostructures at low temperatures. Two opposite types of PPC effects have been observed under different illumination conditions. Specifically, the two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructure samples usually shows a positive persistent photoconductivity (PPPC), namely, the electron density increases after illuminations. Such PPPC effect is due to the existence of DX centers[13] in the AlGaAs barrier. At low temperatures, the photo-excited electrons transfer from DX centers to the potential well by illuminations, which give rise to an increase of the electron density. A prototype of the persistent photoconductivity effect observed in InAs QWs is from the bipolar behavior.[14–17] PPPC can be observed with low photon energy illuminations, whereas the negative persistent photoconductivity (NPPC) appears under illumination with high photon energy.[18–22] The relevant boundary of photon

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energy is supposed to relate with the band gap of GaSb and the valence band offset at the interface between the cap layer and the top barrier.[14]

In this Letter we report the experimental results of the PPC effect in InAs/GaSb and InAs/GaInSb QWs. Based on the fact that the carrier densities can be changed by illuminating light, we tune the samples into the band hybridization phase solely by the PPC effects. The wafers in our experiments are grown by molecular beam epitaxy (MBE) on conductive GaSb substrates, which act as natural back gates. The wafer structures are shown in Fig. 1(a) and (b). The first wafer (panel (a)) includes a 12 nm InAs layer and an 8.5 nm GaSb layer. The second wafer (panel (b)) includes a strained-layer InAs/GaInSb QW, which consists of an 8 nm-thick InAs layer and a 4 nm-thick $Ga_{0.68}In_{0.32}Sb$ layer, with modulation doping in the AlGaSb barriers. Our devices are fabricated with desired geometry by standard ultraviolet (UV) lithography and wet etching techniques. The Ohmic contacts are made by soldering indium or E-beam evaporating Ge/Pd/Au metal films. Transport measurements are performed in a He-3 refrigerator with a base temperature of $T \sim 300$ mK and standard low frequency (17 Hz) lock-in techniques. LEDs with different colors are mounted near the devices, and constant currents (< 1 mA) are applied to the LEDs for illuminations. After each illumination, we wait until the sample resistance becomes stable at base temperature.

The prototype of SdH oscillation features before and after LED illuminations on a 75 µm × 25 µm Hall bar device of the InAs/GaSb QWs is shown in Fig. 2(a), and the relation between electron concentration $n$ and mobility $\mu$ is illustrated in the inset. Before illumination, the $n$ value of the sample is around $\sim 3.1 \times 10^{11}$ cm$^{-2}$. After infrared (IR) LED (with a photon energy of ~ 1.3 eV) illuminations, the sample shows PPPC, and the density $n$ raises to $\sim 3.6 \times 10^{11}$ cm$^{-2}$. With red LED (photon energy ~ 2 eV) illuminations, the sample exhibits NPPC effect. The illumination effect is cumulative, therefore $n$ can be tuned in series from $3.1 \times 10^{11}$ cm$^{-2}$ down to $1.74 \times 10^{11}$ cm$^{-2}$ by different illumination time with red LED. PPC shows the change of electron density persists at low temperatures. At high magnetic fields ($B > 2$ T), the SdH oscillations, shown in Fig. 2(a), start to deviate from the standard single carrier behavior, most likely due to the mixture with the hole oscillations. In addition, Fig. 2(b) shows the longitudinal resistance $R_{xx}$ and Hall resistance $R_{xy}$ versus perpendicular magnetic field $B$ after red LED illumination with a current of 50 µA. At this low electron density of n $\sim 0.8 \times 10^{11}$ cm$^{-2}$, we observe that the filling factor $\nu = 2$ Hall resistance (near 2 T) $R_{xy}$ is substantially smaller than quantized value of $e^2/2h$, again suggesting that the sample is in the two-carrier transport regime, in other words, we have an inverted bulk band structure. After further illuminations with red LED, the device (including the Hall bar arms) becomes very resistive, indicating that the Fermi level is approaching the bulk hybridization gap. Similar phenomenon is observed with blue LED (with a photon energy of ~ 2.6 eV). Moreover, when the Fermi level was tuned close to the bulk gap, the electron density returns to $\sim 3.6 \times 10^{11}$cm$^{-2}$ by illumination with IR light. This property suggests the PPC effect in InAs/GaSb QWs is reversible to some degree. In addition, after sufficient illumination the change of carrier densities will be saturated, which shows that the tuning by PPC effects has its limitations. The carriers in this particular wafer cannot be tuned into $p$-type with LED illuminations.

Previous studies[14–17] provide some explanations for the PPC effect in the InAs QW. The analysis in Ref. 14 is under the condition that eighty percent of electrons in quantum well are originated

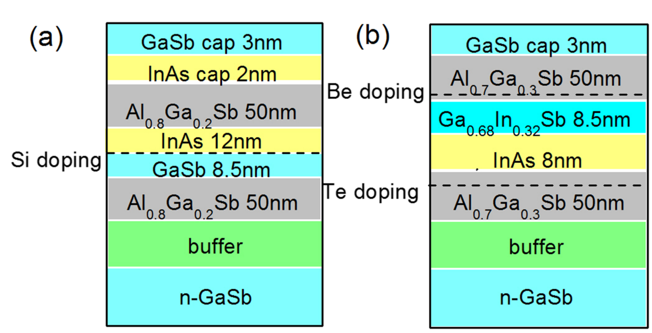


FIG. 1. Wafer structures of (a) the InAs/GaSb QWs and (b) the InAs/$Ga_{0.68}In_{0.32}Sb$ QWs used for our experiments.

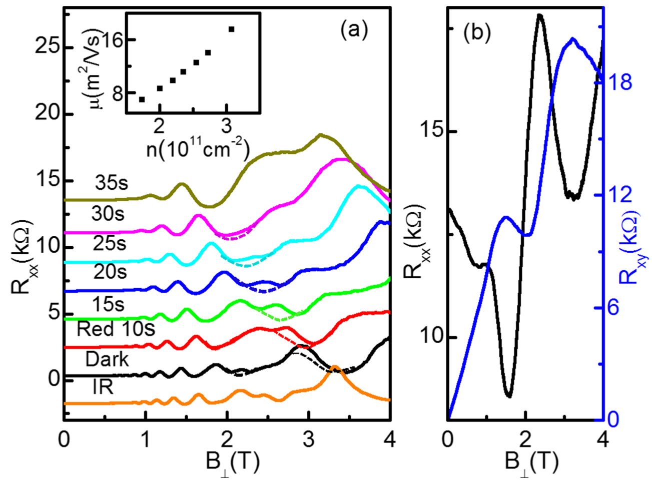


FIG. 2. Persistent photoconductivity effects of the 75 μm × 25 μm Hall bar made by the InAs/GaSb QWs. (a) A series of SdH oscillations after illuminations by IR LED (50 μA) and red LED (10 μA) with different durations, the traces are shifted in turn by +2 kΩ (or -2 kΩ) for clarification. At $B > 2$ T, the traces deviate from the standard SdH oscillations of single carrier, which are described cursorily with dotted lines in the figure. The $n - \mu$ relation is shown in the inset. (b) The $R_{xx}$ vs. $B$ and $R_{xy}$ vs. $B$ traces of the density $n \sim 0.8 \times 10^{11}$ cm$^{-2}$, exhibit strong mixture between $R_{xx}$ and $R_{xy}$ due to the coexistence of electrons and holes. All data is collected at $T \sim 300$ mK.

from the GaSb cap. A similar case is observed in InAs/GaSb double quantum wells. Most electrons in heterostructure come from surface donors in the GaSb cap, others are from the neighboring GaSb quantum well. During illuminations with red LED, electron-hole pairs are excited in the cap layers. The photo-generated holes overcome the band offset at the interface of top barrier and cap layer, and then diffuse towards QWs to recombine with electrons under the assistance from the gradient of the built-in electric field. Meanwhile the photo-generated electrons are trapped by surface donors. When the device is illuminated by an IR LED with smaller photon energy, it is difficult for the photo-generated holes to overcome the potential barrier due to the smaller photon energy from LED. However, the infrared photon energy is high enough to ionize the deep donors in the AlGaSb barriers, producing the PPPC effect.

The main results of the PPC effect in a 75 μm × 25 μm Hall bar in the InAs/$Ga_{0.68}In_{0.32}Sb$ QWs are presented in Fig. 3. We illuminate the sample with LEDs with different colors in order (from low to high photon energy). For each color, the sample is illuminated until the changes of the longitudinal resistance $R_{xx}$ are saturated. Figure 3(a) shows the back gate voltage $V_{bg}$ versus $R_{xx}$ traces with different color LED illuminations. The inset of Fig. 3(a) shows an optical micrograph image of our Hall bar device, where the arms are covered by metals. When the Fermi level is in the bulk hybridization gap in the sample with the insulating bulk states, the measured $R_{xx}$ come from edge states. In our measurements, the InAs/GaInSb QW exhibits an NPPC effect. The Fermi level at zero gate voltage could be tuned from the conduction band into the valence band through the bulk gap. The tuning process is dependent on the photon energy. In addition, the Fermi level can be tuned gradually by varying the illumination time; a longer time gives rise to a stronger NPPC, as illustrated in Fig. 3(b). Similar to the InAs/GaSb QWs, the PPC effects of InAs/GaInSb QWs are also reversible. For instance, at $V_{bg} = 0$ V, an InAs/$Ga_{0.68}In_{0.32}Sb$ sample can be tuned into $p$-type with green light, but with IR illuminations the electrons can return to the TI phase.

A prominent advantage of the InAs/GaSb and the InAs/GaInSb QSHI system is that the bulk band structure can be tuned by electric fields. Besides tuning the Fermi level, the PPC effect can change the bulk band structure, because the built-in electric field caused by charge transfer are directly affected by illuminations. We perform magneto-transport to deduce the $n_{cross}$ value for another 75 μm × 25 μm Hall bar made on the InAs/GaInSb QWs, as shown in Fig. 3(c). The $n_{cross}$ value before and after red LED illuminations is $\sim 2.8 \times 10^{11}$ cm$^{-2}$ and $\sim 2.1 \times 10^{11}$ cm$^{-2}$, respectively. It suggests that the bulk band becomes less inverted after red LED illuminations. The edge coherence length increases with the decrease of $n_{cross}$ (Fig 3(a)), which is consistent with our previous results.[9]

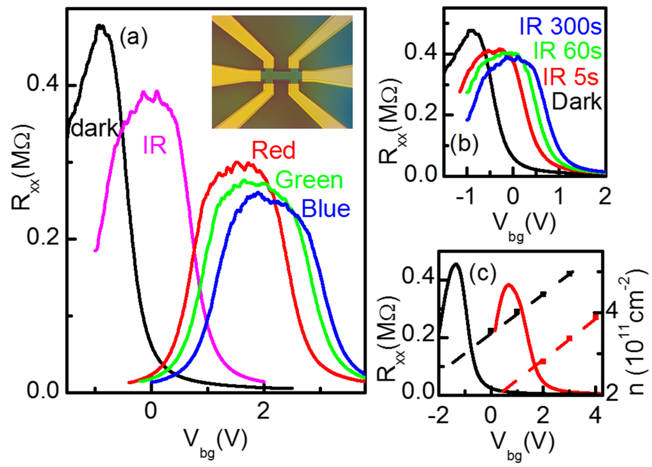


FIG. 3. (a) $R_{xx}$ vs. $V_{bg}$ traces of a 75 µm × 25 µm Hall bar under illuminations with different color LEDs. The $R_{xx}$ peak moves from negative $V_{bg}$ to positive $V_{bg}$ with gradually increasing photon energy of illumination, which means the Fermi level at $V_{bg}$ = 0 V could be tuned from the conductive band to the valence band through the bulk hybridized gap. The inset shows the optical microscope image of the device. (b) $R_{xx}$ vs. $V_{bg}$ traces after illuminations by IR LED (constant current ~ 0.1 mA) with different time. (c) $R_{xx}$ vs. $V_{bg}$ traces of another 75 µm × 25 µm Hall bar before and after the red LED illuminations. The squares represent the electron density deduced from the SdH oscillations at different $V_{bg}$. All data is taken at $T$ ~ 300 mK.

We further investigate the PPC effect in a Corbino device made on the InAs/GaInSb QWs. Compared with the Hall bar device, the resistances measured are solely due to bulk states since the edge states are shunted by circular electrodes as shown in Fig 4(a). Fig 4(b) shows the temperature-dependent measurements of the resistance per square after tuning the Fermi level into the bulk gap by only illuminations, where the bulk resistance per square is larger than 10 MΩ at $T$ ~ 300 mK. The energy gap can be roughly deduced from the Arrhenius plot by fitting the equation: $G_\square \propto \exp(-\Delta/2k_BT)$ at low temperatures, where Δ is the bulk gap energy and $k_B$ is the Boltzmann constant. We obtain an energy gap of Δ ~ 192 K, which is in agreement with the previous report.[9] In our study, all the PPC effects disappear when the sample temperature increases to room temperature, and the transport properties do not change after re-cooling.

A major difference between the InAs/GaSb QWs and the InAs/GaInSb QWs on the PPC effect is their response to the IR illumination. The difference is caused by the doping structure. The carriers in the InAs/GaInSb QWs are mainly from the intentional dopings, rather than from the top cap. The energy band layout of InAs/GaInSb QWs is shown in the inset of Fig 4(b). The electron and hole wave

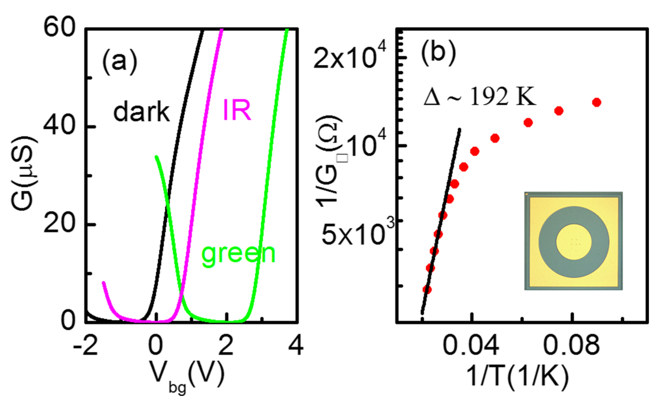


FIG. 4. (a) The conductance per square $G_\square$ versus $V_{bg}$ of a Corbino device made by the InAs/ $Ga_{0.68}In_{0.32}Sb$ QWs under illuminations with different photon energy, measured at $T$ ~ 300 mK. (b) The Arrhenius plot measured at $V_{bg}$ = 0 V after illuminations. The bulk gap can be deduced by fitting $G_\square \propto \exp(-\Delta/2k_BT)$ at higher temperature. The inset shows the optical microscope image of the Corbino device.

functions overlap in InAs and GaSb layers in the strained QWs. Because of the larger effective mass of holes, the band hybridization mainly comes from the electron wave function (from InAs layer) extention into the GaSb layer. Under illuminations, the electrons in quantum well will recombine with the holes from photo-ionizations of acceptor doping in top barrier. The illuminations also contribute to donor ionizations in bottom barrier, there exists a competition between doping ionization from the top and bottom barriers.

In summary, we demonstrate that the PPC effects can tune both the Fermi level and the band structure of InAs/GaSb QWs and InAs/GaInSb QWs. It offers a simple and reliable method to control the band structure and charge states in these matters. Comparing to traditional gating method, the PPC technique provides another knob to manipulate the potential topological states in the composite heterostructures, such as InAs/GaSb and InAs/GaInSb QWs.

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